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RESEARCH MEMORANDUM

PRELIMINARY EVALUATION OF PENTABORANE IN A 1/4-SECTOR OF AN EXPERIMENTAL ANNULAR COMBUSTOR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A 1/4-sector of an annular combustor designed for use with pentaborane fuel was evaluated at a simulated altitude condition. The combustion efficiency was about 100 percent. The pressure drop was 2.8 percent of the inlet total pressure. The rate at which boron oxide collected was less than one-fifth that of a standard can combustor (with modified fuel injectors) operating at comparable conditions. The variations in the combustor outlet temperature were slightly greater than normal practice.

A brief test with JP-5 fuel indicated that JP-5 can be used satisfactorily in this combustor.

INTRODUCTION

Aircraft fuels having high chemical heating values have been the subject of intensive research in recent years (refs. 1 and 2). Among the fuels of interest are the boron hydrides. A typical boron hydride, pentaborane, has been made available to the NACA Lewis laboratory by the Bureau of Aeronautics, Department of the Navy, and more recently by the U. S. Air Force.

Several tests with pentaborane fuel have been conducted in a J47 turbojet engine located in an altitude test facility. These tests have shown that by using pentaborane the specific fuel consumption of a turbojet engine can be reduced to two-thirds that of JP-5 fuel. However, in all tests the engine performance began to deteriorate after 1 to 2 minutes operation on pentaborane (refs. 2 and 3).

The cause of this performance deterioration is the boron oxide formed when boron-containing fuels are burned; 2.75 pounds of boron oxide are formed for every pound of pentaborane burned. Boron oxide is an extremely viscous liquid at normal turbojet operating conditions and is a glass-like solid at temperatures below 900° F.

The boron oxide is initially in the vapor form in the combustor. It condenses in the form of microscopic drops. The microscopic drops flow with the gas unless contacted by a surface. The amount of oxide formed as films is proportional to (1) the amount of surface seen by the microscopic drops and (2) the concentration of the oxide (refs. 4 and 5). If the concentration of the films and large drops is too high to be eroded away by the dynamic force of the gas stream, performance losses occur. The engine can evidently tolerate a reasonable amount of large drops and films, as established by a full-scale engine test of trimethylborate fuel. This fuel, which produces 3/8 the concentration of boron oxide in the gas stream compared with pentaborane, caused little change in performance after an 80-minute test run (ref. 3). 4063

It then follows that, if the amount of oxide collected as films and large drops can be substantially reduced, pentaborane fuel performance should not deteriorate. Since the turbine stator and rotor performance suffers the most (ref. 3), it is important that the oxide be kept from collecting on the combustor and combustor transition surfaces upstream of the turbine.

An early attempt to reduce the amount of heavy oxide entering the turbine is reported in reference 6. The combustor length was reduced and a large part of the combustor was fabricated out of wire cloth. The air film coming through the porous wall kept the oxide from depositing on these surfaces. The full-scale engine tests of this combustor (ref. 3) were unsatisfactory because of the poor combustor-outlet temperature profile.

The purpose of this report is to present the design concepts and performance data of a new pentaborane combustor design. This combustor is designed to reduce the formation of the type of boron oxide deposit that causes performance deterioration. The combustor tested in this investigation had the following characteristics: a short annular combustor shape, air-filmed combustor surfaces produced by continuous louvers, and secondary-air mixing slots for control of temperature profile. The combustor is attached directly to the turbine nozzle station in order to eliminate transition surfaces.

The combustion efficiency, outlet temperature profile, pressure drop, and deposit ratio are presented for a single test of pentaborane fuel. Data for JP-5 fuel are also included.

APPARATUS

Combustion Installation

The combustion air was passed through a heat exchanger and then was metered to the test installation (fig. 1). Combustion products were discharged to an exhaust system at atmospheric pressure.

The combustor shown in figure 2 was 1/4-sector of an annular combustor designed to fit the housing diameter and turbine nozzle annulus dimensions of a J47 turbojet engine. The dimensions are also similar to a J65 turbojet engine. Figure 3 is a photograph of the combustor and dome.

Fuel Nozzles

The fuel nozzle assembly is shown in figure 4. It consisted of a 6-port air-atomizing nozzle with a cone angle of 70°. Twelve of these nozzles were used in the 1/4-sector and were directed normal to the air stream.

Instrumentation

The instrument stations are shown in figure 1. The arrangement of thermocouples and total-pressure probes is shown in figure 5. Temperatures were measured by bare-wire chromel-alumel thermocouples. Fuel flow was measured by a rotating-vane flowmeter.

Fuel System

The fuel and atomizing-air systems are shown schematically in figure 6. The JP fuel was used to flush the fuel lines and nozzles immediately before and after the pentaborane test.

PROCEDURE

The 1/4-sector tests were made at the following conditions:

Combustor-inlet temperature, °F	372
Combustor-outlet temperature, °F	1500
Combustor-inlet total pressure, in. Hg abs	32
Air flow, lb/sec	4.53

These combustor conditions closely simulate the following flight conditions of a J65 turbojet engine:

Altitude, ft	55,000
Mach number	0.8
Engine speed, percent of rated	100

For the pentaborane test, the fuel nozzles were first flushed with JP fuel, and the pentaborane turned on and ignited. Data were taken at 1-minute intervals. JP-5 test data were taken at about 10-minute intervals.

CALCULATION METHODS

Combustion efficiency was calculated by comparing actual to theoretical fuel flow for the same temperature rise across the combustor:

$$\eta_b = \left(\frac{w_{f_{theoretical}}}{w_{f_{actual}}}\right) \times 100, \text{ percent}$$

The temperature rise across the combustor was based on the arithmetic 4063
average of the thermocouples located at the combustor outlet. The arithmetic averages do not necessarily correspond to a mass-weighted average temperature, so the efficiency may be in error. Reference 7 has shown efficiency based on an arithmetic average temperature may be 10 percent high. The degree of error is, of course, dependent on the outlet velocity profile. Since local velocities were not measured at each thermocouple, this form of error has not been determined in this experiment. Other errors are introduced by the unknown effect of boron oxide on radiation, convection, and conduction on thermocouple readings. Since these errors exist, an additional check on the efficiency of pentaborane was made by examining the boron oxide deposits in the combustor outlet for unburned boron.

RESULTS AND DISCUSSION

The results of the pentaborane and JP-5 fuel tests are given in table I.

Pentaborane performance. - A synopsis of the pentaborane fuel performance is as follows:

Combustion efficiency, percent . . . . 103 (+0, -10, see above)
(No evidence of unburned boron in deposits)
Combustor pressure drop, $\Delta P/P$, percent 2.8
Deposit ratio, $\frac{\text{Weight deposits in combustor}}{\text{Weight oxide formed by combustion}}$ 0.00134

The outlet combustor temperatures are shown in figure 7. The temperatures shown were taken 2 minutes after the start of the test. The radial profiles based on the average of the circumferential profiles are shown in figure 8. Included in figure 8 is a typical radial profile of a standard J65 combustor. This profile is based on the average of four radial measurements made during a full-scale engine test with JP-5 fuel at similar test conditions. The radial temperature profiles of the 1/4-sector are similar to those of the standard combustor. The circumferential temperature spread (fig. 7) is greater than desirable. Part of the variation in circumferential profile may be due to unbalanced fuel flows in the fuel nozzles.

Photographs of the combustor after the test are shown in figures 9(a) and (b). The total deposit weight was only 21 grams, and this deposit was soft and powdery. Most of the deposit was located downstream of the secondary-air slots. The heavy deposit on the untreated side wall (fig. 9(b)) was not included in the deposit weight. This deposit on the side wall is similar to deposits formed in conventional combustors operated with pentaborane fuel. The deposit ratio in the new combustor is 0.00134, as compared with 0.0075 for the standard combustor (ref. 5) and 0.0036 for the wire-cloth combustor (ref. 6) at similar operating conditions.

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Although the deposits were very light in the new combustor, the combustor is sensitive to minor departures from the basic design. For example, the upstream dome was fabricated from perforated sheet steel. At one spot on the dome the perforated sheet metal was pieced together by welding. The weld closed one row of holes. At the weld location a small amount of boron oxide began to form (fig. 9(a)). Since potentially large deposits can follow malfunctioning of any combustor part, extreme care in design and fabrication of the combustor is necessary.

Combustor development. - Several combustor designs were tested leading to the development of the final configuration. From the start the louvered construction was used in order to film the combustor walls with air. The louvered-wall construction was used instead of the wire cloth (ref. 6), since louvers appeared to be more reliable and more adaptable to production. The short annular combustor design was selected to minimize combustor surface. Air was bled in through perforations in the dome to reduce recirculation in the combustor. Since pentaborane tends to decompose if exposed to the high combustor temperatures, the fuel injectors were located on the outer wall. Air-atomizing nozzles similar to those described in reference 5 were used. The atomizing air performs these special functions: (1) cools nozzle, (2) reduces "coking" on the outer surface of the nozzle, (3) atomizes the fuels, and (4) controls fuel penetration. The major variations in the combustor design were made by changing the ratio of air through the dome, louvers, and secondary-air mixing slots. Early trials were made without secondary-air mixing slots, but the spread in the radial temperature profile was unacceptable. The secondary-air slots were alternately spaced on the top and bottom of the combustor in order to promote circulation and thus mixing of the combustion gases. The proportion of open areas entering the combustor that has given the best results to date are:

Combustor part	Physical area, sq in.	Corrected flow area (coefficient assumed), percent
Dome	17.7	18.2
Louvers on outer surface	14.8	15.3
Louvers on inner surface	9.8	10.1
Slots on outer surface	20.4	28.2
Slots on inner surface	20.4	28.2

The air through the louvers was metered through a row of small holes as shown in figure 2. Narrow slots on the upstream edge of the louvers were used in early tests. These slots were abandoned because they distorted with mechanical and thermal loads.

JP-5 Fuel performance. - In full-scale tests of pentaborane it is desirable to operate the engine on JP-5 fuel during calibration and warm-up periods. Also, in flight operation it may be desirable to operate the engine on both fuels. Although the objective of this experiment was to develop a combustor for pentaborane fuel, a preliminary test with JP-5 fuel was made in order to evaluate the possibility of a dual-fuel combustor. The results are as follows: 4063

Combustion efficiency, percent	97 to 100 (+0, -10)
Combustor pressure drop, $\Delta P/P$, percent	2.8
Combustor-outlet temperatures	fig. 10
Radial temperature profile	fig. 11

It was necessary to change the positions of the sparkplug from the location used with pentaborane fuel. The spark electrodes were extended into the JP-5 fuel spray in order to obtain reliable ignition.

The performance of the combustor with JP-5 fuel is considered acceptable.

CONCLUDING REMARKS

The preliminary test of an annular combustor designed for pentaborane fuel indicated the performance was satisfactory for limited use in a research engine. The combustion efficiency was about 100 percent. The pressure drop was 2.8 percent of the inlet total pressure. The rate at which boron oxide collected was less than one-fifth that of a standard can combustor (with modified fuel injectors) operating at comparable conditions. The variations in the combustor-outlet temperature were slightly greater than normal practice.

A brief test with JP-5 fuel indicated that JP-5 can satisfactorily be used in this combustor.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, February 13, 1956

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TABLE I. - SUMMARY OF DATA

Run duration, min	Fuel	Time data recorded, min	Combustor-inlet total temperature, °F	Combustor-inlet total pressure, in. Hg abs	Air flow,[a] lb/(sec)(sq ft)	Fuel flow, lb/sec	Average combustor-outlet temperature, °F	Combustor inlet velocity, ft/sec	Atomizing air flow, lb/sec	Combustion efficiency, percent	Pressure loss across combustor, $\Delta P/P_i$	Deposit weight at end of run, g	Fuel burned, lb
4.5	Pentaborane	1.0	377	32.0	3.60	0.0470	1494	70.8	0.0545	103.5	0.028	21	12.5
		2.0	372	32.1	3.62	.0470	1493	70.5	.0545	103.7	.026		
		3.0	370	32.1	3.62	.0469	1482	70.4	.0545	103.0	.028		
		3.7	372	32.1	3.60	.0465	1477	70.2	.0545	102.0	.028		
---	JP-5	---	370	31.6	3.51	.0820	1450	69.4	.0472	96.0	.027	--	----
		---	370	31.6	3.51	.0815	1390	69.4	.0472	102.0	.027		

[a]Combustor housing cross-sectional area, 1.25 sq ft.

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[redacted]

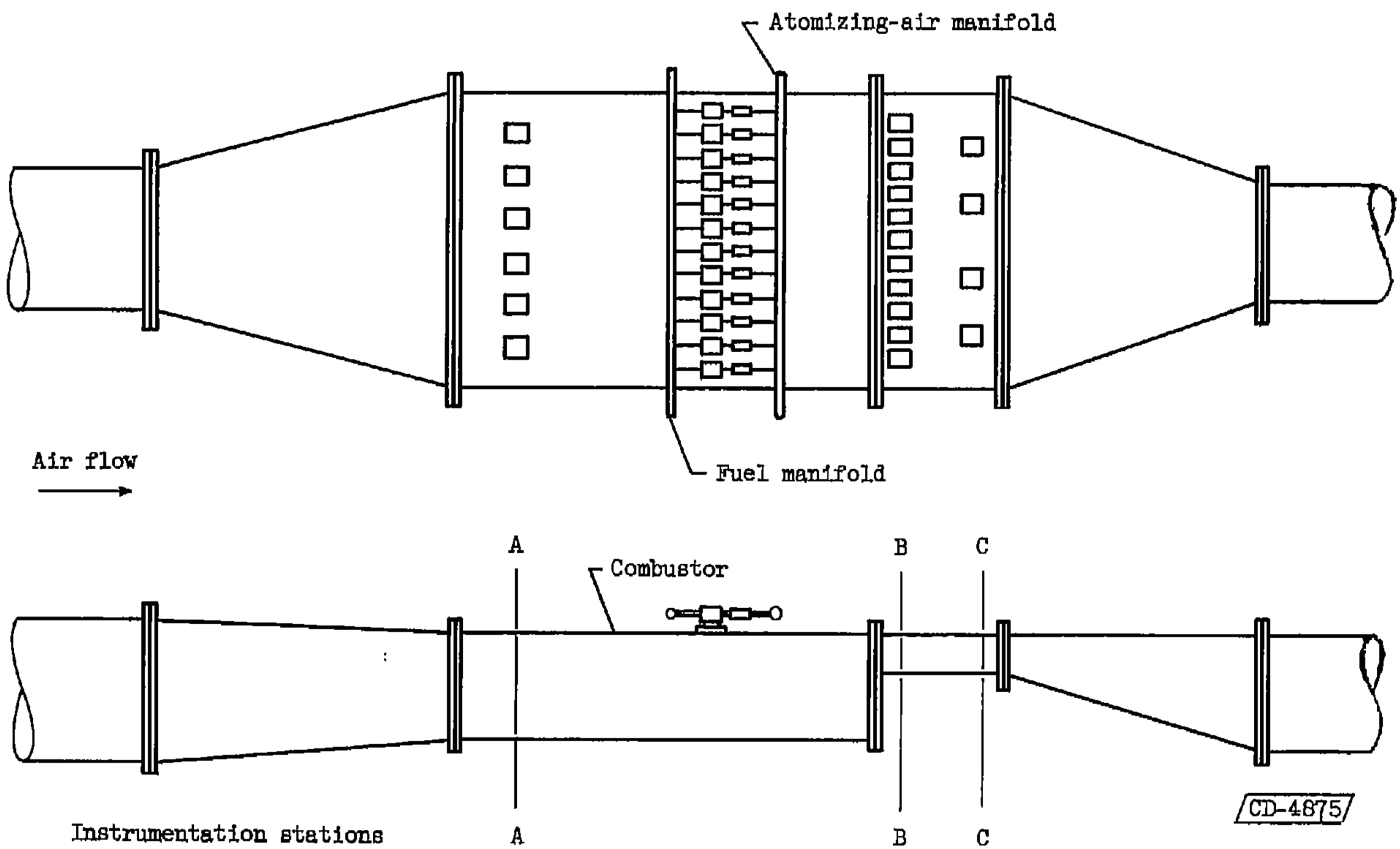

Figure 1. - Schematic diagram of test installation.

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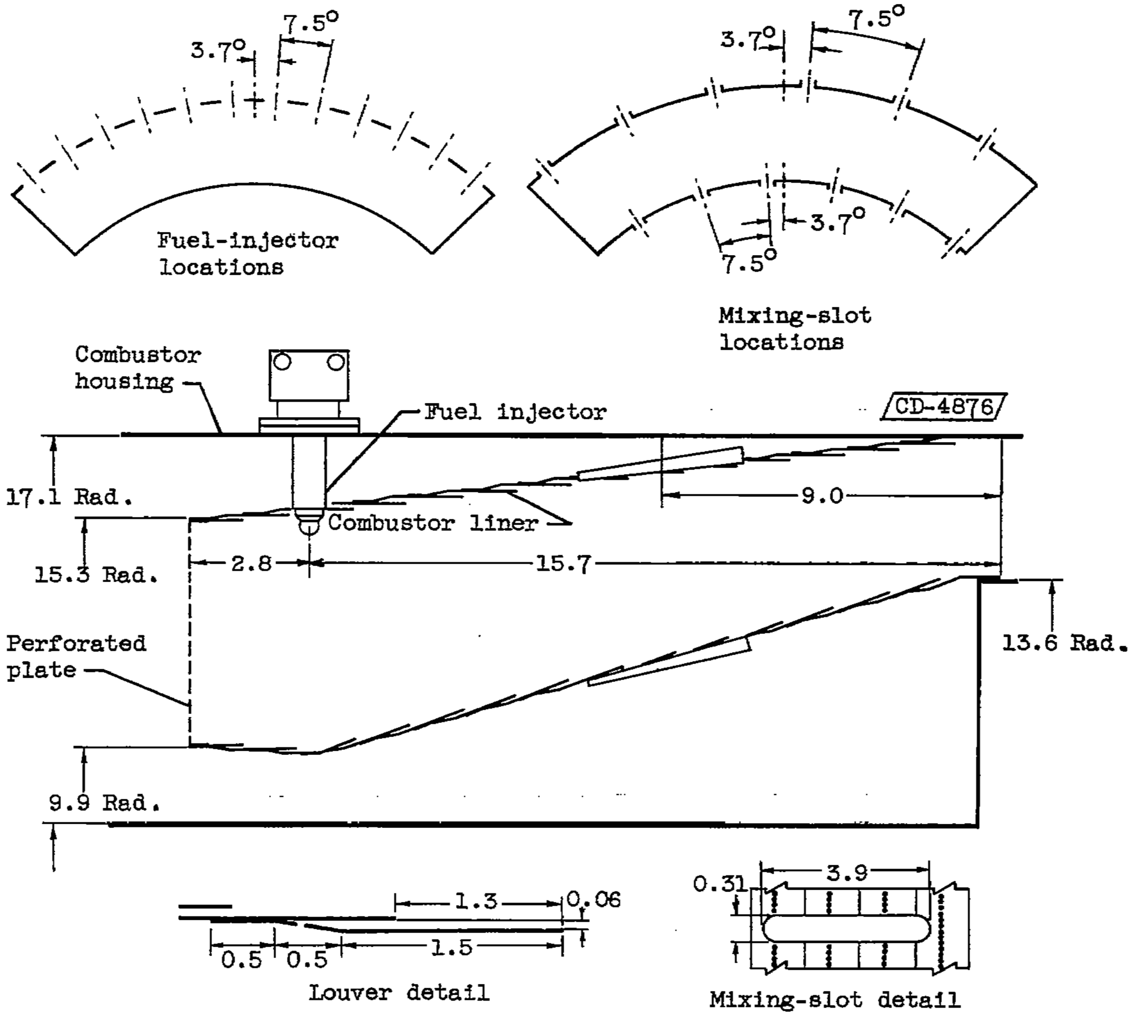

Figure 2. - Diagram of 1/4-sector of annular combustor.
(All dimensions in inches.)

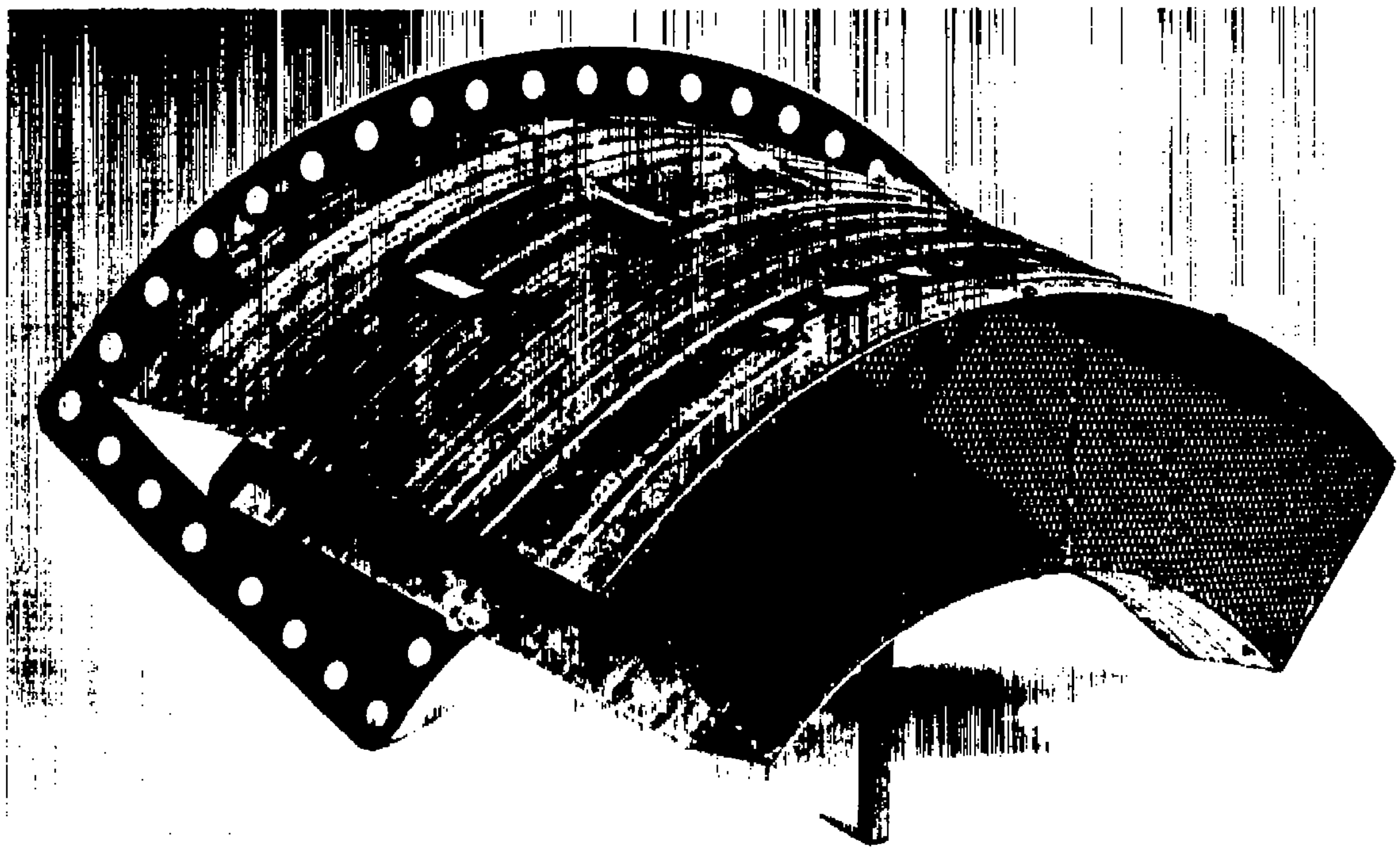

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Figure 3. - Experimental combustor.

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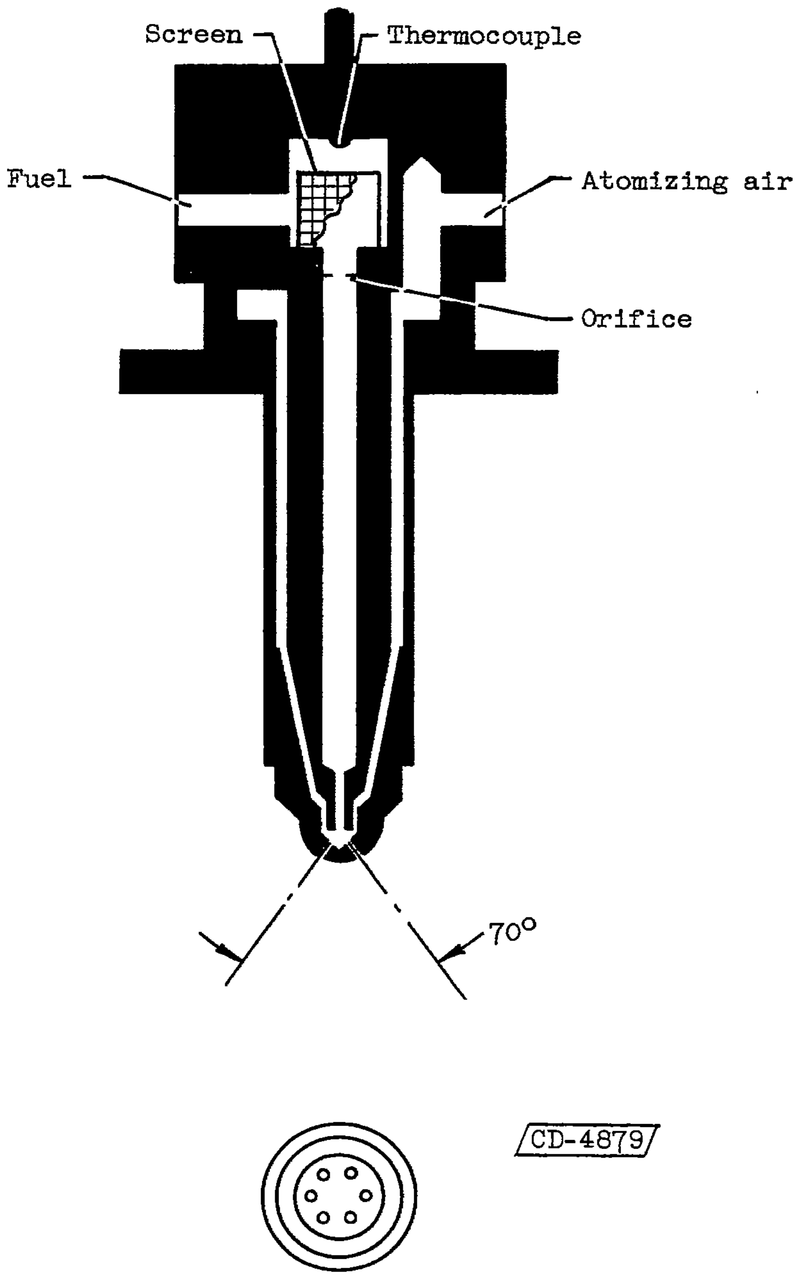

Figure 4. - Fuel nozzle assembly.

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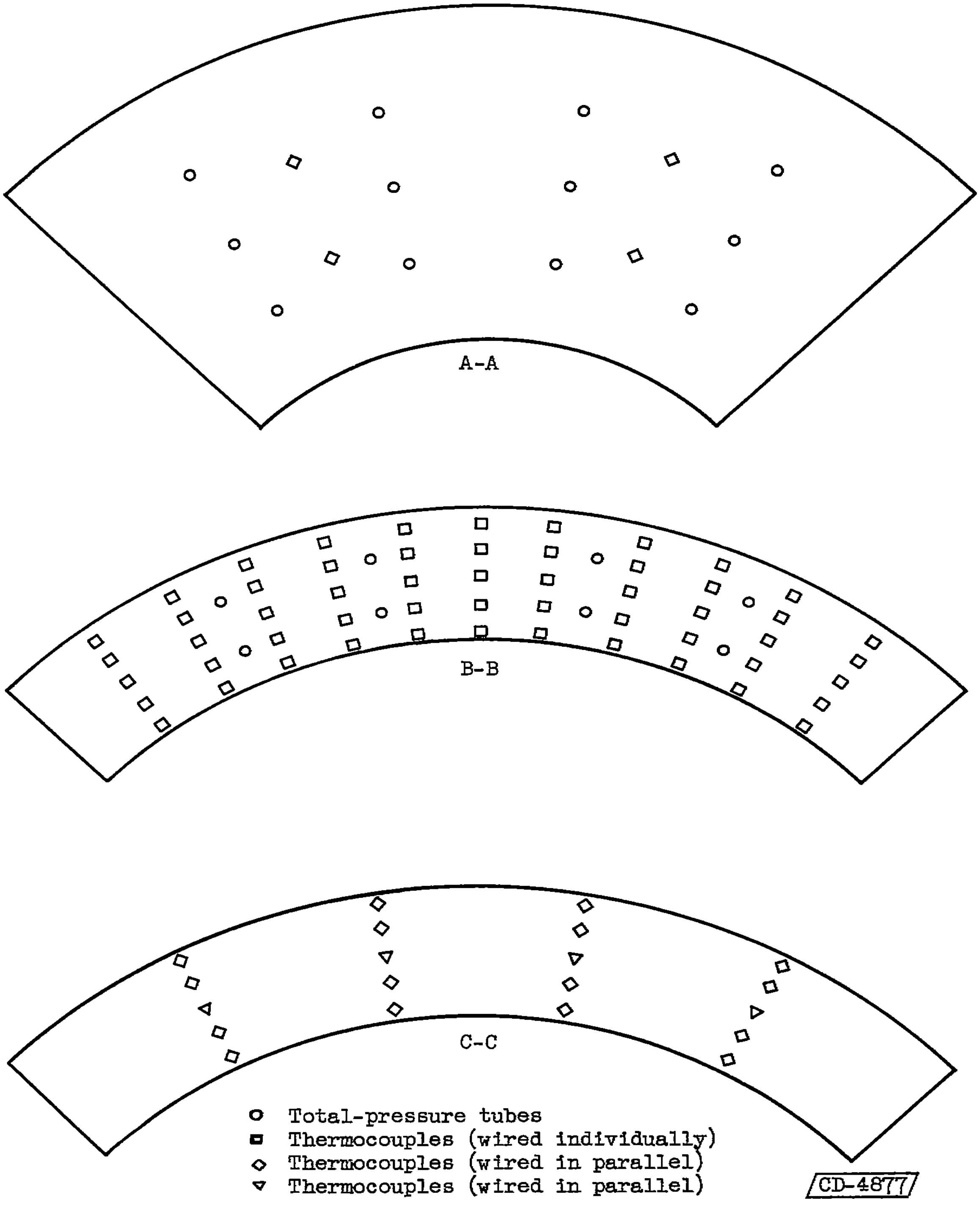

Figure 5. - Location of thermocouples and total-pressure probes at combustor outlet.

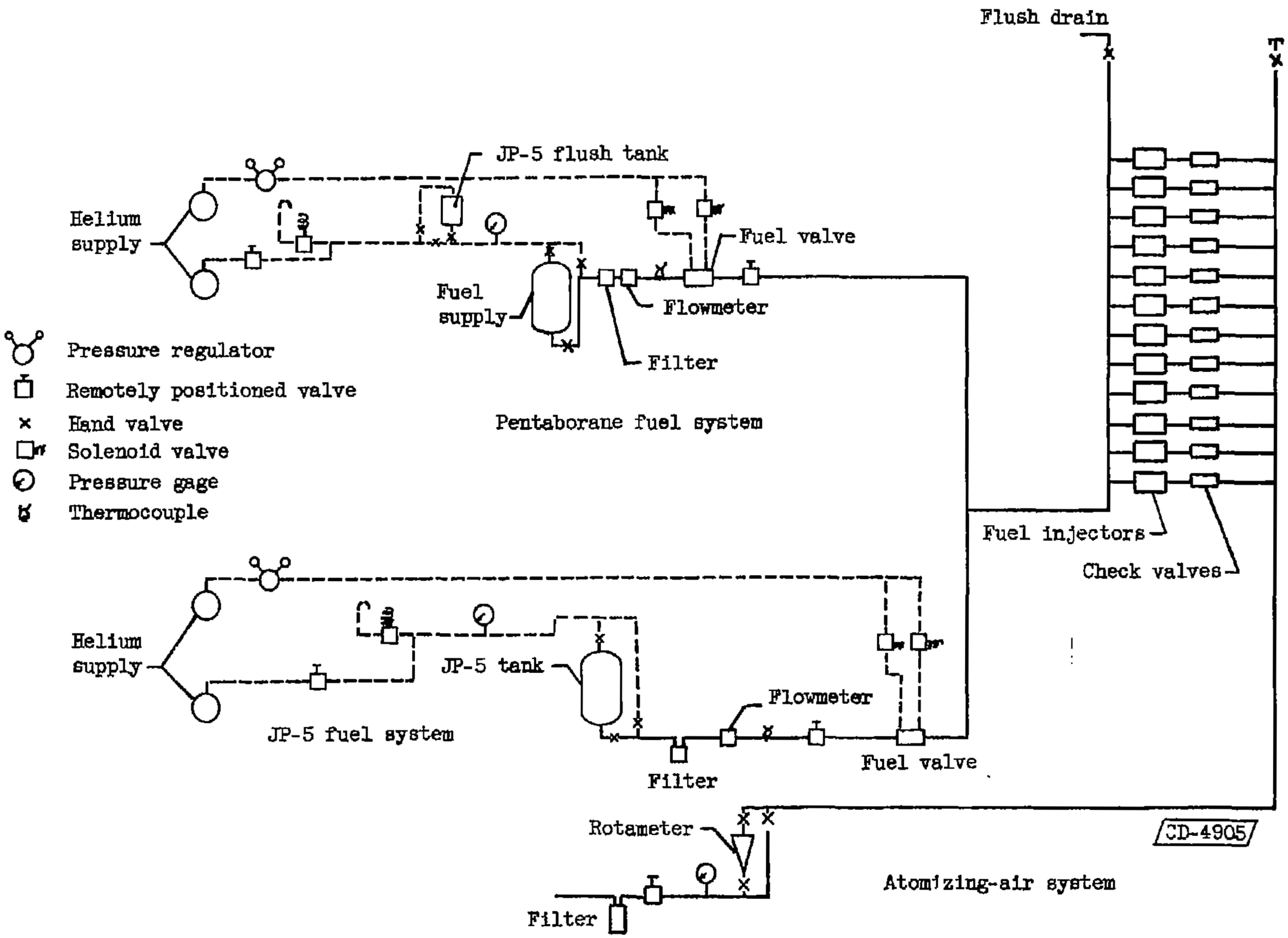

Figure 6. - Fuel and atomizing-air systems.

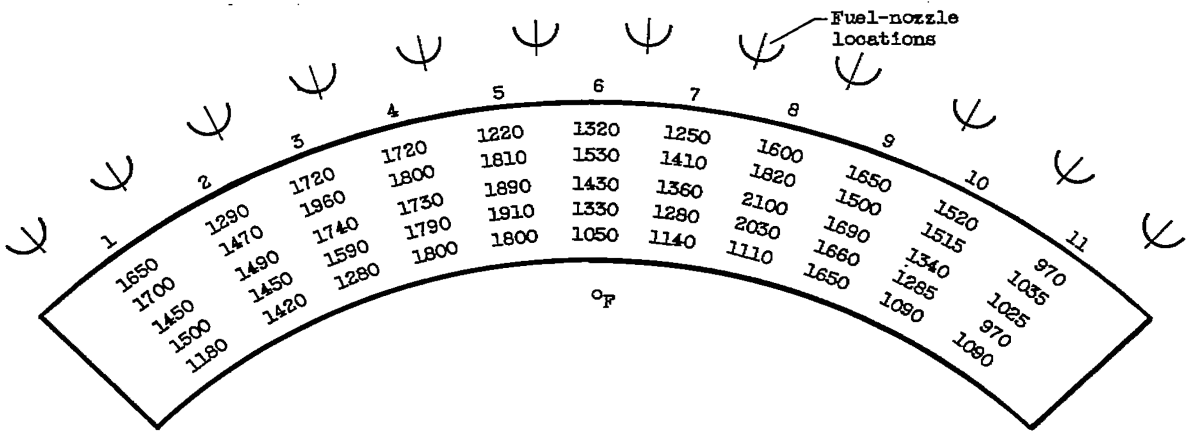

Figure 7. - Survey of combustor-outlet temperatures with pentaborane fuel.

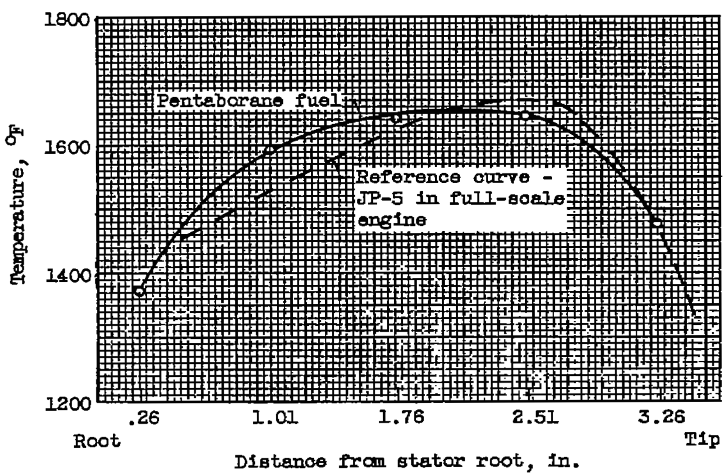

Figure 8. - Radial temperature profile with pentaborane fuel.

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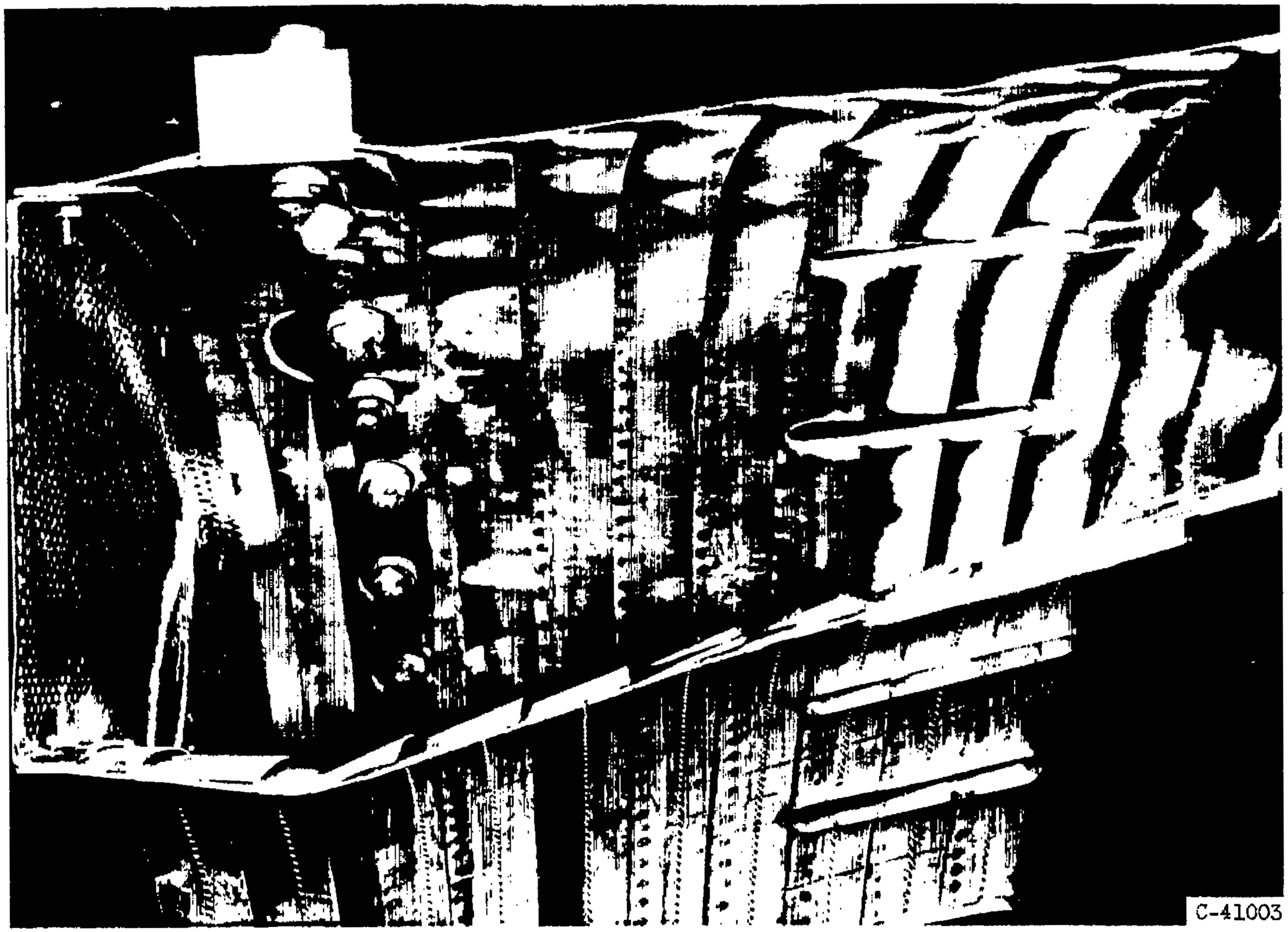

(a) Side view.

Figure 9. - Combustor after burning 12.5 pounds of pentaborane fuel.

(b) View of untreated side wall.

Figure 9. - Concluded. Combustor after burning 12.5 pounds of pentaborane fuel.

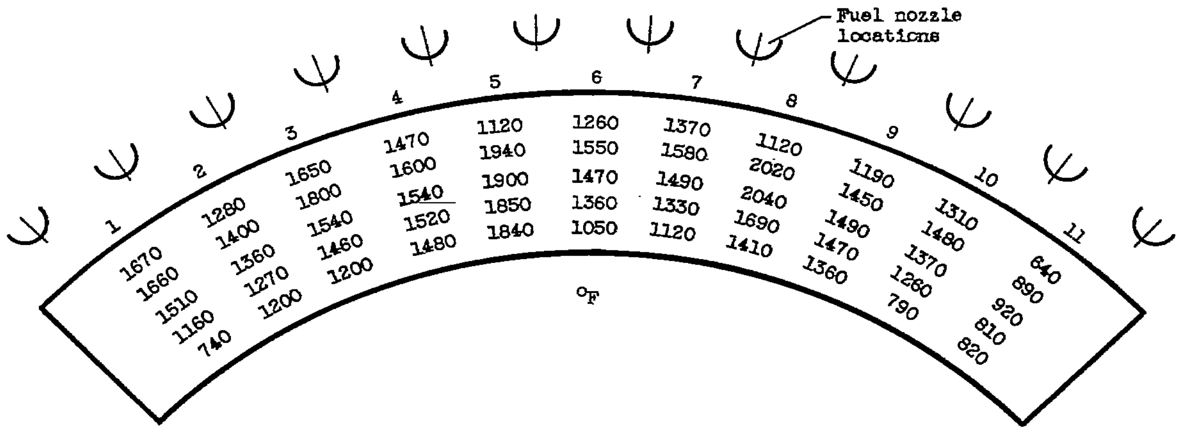

Figure 10. - Survey of combustor-outlet temperatures with JP-5 fuel.

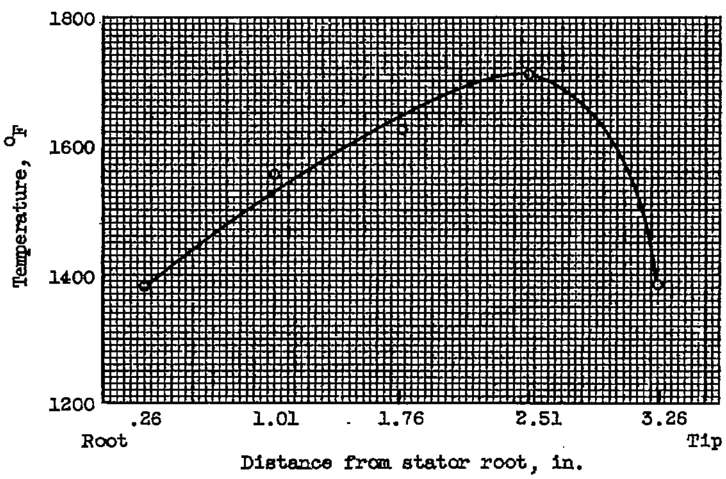

Figure 11. - Radial temperature profile with JP-5 fuel.

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